FACTORS INFLUENCING THE LIKELIHOOD OF CONTINUATION OF INTERNAL EROSION

DATE: JULY 2012

Factor	**Influence on Likelihood (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Filter Presence / Embankment zoning – Is there a zone of material that would serve as a filter? (see also “Materials downstream of filter” below).	Zoned embankment dam. Dam with a well-designed and constructed filter. Much less likely if the design includes a two-stage filter and drain.	There is a granular zone downstream of the impervious zone that was not specifically designed to filter (e.g. transition zone, coarse granular zone or dirty shell/rockfill); more geotechnical information is needed to evaluate this condition.	Dam is homogeneous, or there is no zone downstream of the impermeable zone that would serve as a filter (e.g. riprap slope protection or a clean rockfill zone).	This is a broad, general consideration. There is no need for a detailed evaluation of the probability of an unfiltered exit for dams that have no materials that would serve as a filter; i.e. P ~ 1.0.
Filter Gradation - Gradation of the zone immediately downstream of the impervious zone if there is no modern designed filter; or the filter gradation if a filter exists.	Average $D_{15}F$ satisfies no erosion criteria. Much less likely if the coarsest $D_{15}F$ satisfies no erosion criteria.	Most of the $D_{15}F$ satisfy no erosion criteria for most of the impervious zone gradations, and the coarsest $D_{15}F$ is less than the excessive erosion boundary. Some embankment designs in the 1950s and 1960s included wide, broadly-graded filters (sometimes called “transition zones”). These gradations may or may not satisfy no erosion criteria and they are likely subject to segregation during construction; a detailed evaluation is warranted considering the potential for extensive areas of cobbles with little or no finer material. This would be of more concern at the top of a dam where this zone might be narrower than lower in the dam.	Likely if the average $D_{15}F$ does not satisfy no erosion criteria, but the coarsest $D_{15}F$ is less than the excessive erosion boundary. More likely if the average and coarsest $D_{15}F$ are greater than the excessive erosion boundary. Much more likely if the average $D_{15}F$ exceeds the continuing erosion boundary.	Relative guidance is provided here. Judgment is needed to estimate the probability that erosion would continue for materials that do not satisfy no erosion criteria. Generally, if $D_{15}F$ does not satisfy no erosion criteria, but does not exceed the continuing erosion boundary, a detailed evaluation of gradations, and the estimated representativeness of those gradations, is warranted.
Cracking of filter, or zone immediately downstream of the impervious zone, due to fines content and compaction.	Well compacted material with < 5% non-plastic fines. Much less likely for poorly-compacted material with < 5% non-plastic fines.	Poorly-compacted material with 5-15% non-plastic fines. Poorly-compacted material with 5-7% plastic fines.	Well-compacted material with 5-15% non-plastic fines, or poorly-compacted material with >15% non plastic fines. Well-compacted material with 5-7% plastic fines, or poorly-compacted material with 7-15% plastic fines. Much more likely for well-compacted material with > 7% plastic fines or poorly-compacted material with >15% plastic fines.	The descriptors in this row provide guidance on the likelihood of cracking, not solely continuation (adapted from Fell, Wan, Foster 2004). Increased fines content in materials serving as a filter increases the likelihood that a crack will hold. Consideration should be given to fines content and plasticity, particularly for materials not specifically designed as filters but constructed adjacent to impermeable materials. The sand castle test is a simple test that can be used to evaluate the ability of a filter material to collapse or self-heal.

FACTORS INFLUENCING THE LIKELIHOOD OF CONTINUATION OF INTERNAL EROSION				**DATE: JULY 2012**
Factor	**Influence on Likelihood (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Materials downstream of filter	Two stage filter and drain designed such that the drain material satisfies particle retention criteria for the filter. Sufficient overburden pressure on the filter to prevent uplift if a concentrated leak and high pressure develops.	Two stage filter and drain not provided, but materials downstream of filter have gradations that prevent erosion of filter materials. Sufficient overburden pressure on the filter to prevent uplift if a concentrated leak and high pressure develops.	Two stage filter and drain not provided, and materials downstream of filter could allow erosion of filter materials. Insufficient overburden pressure on the filter to prevent uplift if a concentrated leak develops and there is no, or minimal, head loss.	Modern designs typically include a two-stage filter and drain system; however, many Reclamation dams that have not been modified do not have a two-stage system. If a coarse material, such as a rockfill shell, is placed downstream adjacent to a filter, the filter could be eroded into the shell. If the downstream zone could sustain a crack, the filter could be eroded through the crack.
Filter Location	Filter material in direct contact with impermeable zone.	Filter located in a downstream zone, but not directly adjacent to the impermeable zone materials. The zone between the impervious zone and the filter is granular but was not designed as a filter; or it is unlikely to serve as a repository for eroded materials.	Filter located in a downstream zone, but not directly adjacent to the impermeable zone materials. The zone between the impervious zone and the filter could serve as a repository for eroded materials.	Having a filter located downstream, but not adjacent to, the impermeable zone is not an ideal design; however for some modification designs (particularly seismic modifications) it might be necessary. Consideration should be given to the possibility that impervious materials would erode and be deposited in a zone between the impermeable zone and the downstream filter.
Filter Width (horizontal width downstream of impervious zone)	Filter is > 8 ft wide and segregation during construction was minimized. Much less likely if filter is > 12 ft.	Filter is between 4 and 8 ft wide.	Filter is < 3 to 5 ft wide. Segregation considerations are significant for narrow filters. See below. Much more likely if filter is < 1.5 ft wide.	In general wider filters have a greater likelihood of being constructed as a continuous zone. Wider filters also have a smaller likelihood of a continuous coarse zone extending from upstream to downstream. These factors are for static considerations only, not seismic.
Filter segregation during construction	Gradation meets Reclamation segregation design criteria; uniformly graded material. Good quality construction methods to prevent segregation.	Gradation does not meet Reclamation segregation design criteria. However, construction methods employed that limited segregation; use of spreader boxes; hand working materials; good construction inspection. Construction procedures may have resulted in limited areas of coarser materials, but no continuous (upstream to downstream) zones of coarse, segregated materials.	Gradation does not meet Reclamation segregation design criteria. Materials stockpiled; materials dumped from a truck on fill; other construction methods not employed that could limit segregation; limited or no construction inspection. Construction procedures used that could have resulted in a continuous (upstream to downstream) zone of coarse, segregated materials.	Reclamation segregation criteria are provided in the Protective Filter Design Standard (Reclamation 2011a). Segregation could also result in suffusion (see below)
Suffusion – potential for internal instability and erosion of filter materials	Uniformly graded materials.	Well-graded materials or other materials that are not uniformly graded, but not internal unstable.	Broadly-graded materials or gap-graded materials that are potentially internally unstable. Materials with sufficient coarse fraction such that effective stresses are	Broadly-graded materials serving as filters may be subject to suffusion – resulting in a loss of filter compatibility because the filter will no longer retain D15 and smaller

Factors Influencing the Likelihood of Continuation of Internal Erosion				**Date: July 2012**
Factor	**Influence on Likelihood (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
			carried by the coarse fraction, enabling the finer fraction to erode out.	particles.
Gradation testing - both the impervious zone to be filtered, and the materials adjacent to the impervious zone that would serve as a filter.	Many gradation test results available from pre-construction (borrow areas); construction (after compaction) and/or post-construction (as part of a filter evaluation).	Some gradation test results available from pre-construction (borrow areas); construction (after compaction) and/or post-construction (as part of a filter evaluation). Samples may not be completely representative of the materials constructed.	Very limited, or no gradation test results available. Little knowledge about the types of soils or the borrow areas used during construction.	Gradation test results provide confidence in the ability to evaluate the potential for an unfiltered exit. When there is little or no information available, significant uncertainty is introduced; however, that uncertainty does not automatically mean there is a high probability of an unfiltered exit; rather a large range should be considered until additional information can be obtained and evaluated further.
Toe drains – drains that could provide an unfiltered exit.				Toe drains have presented problems at several Reclamation dams and can serve as an unfiltered exit point. Typical Reclamation designs for many years included open-joint clay tile pipe. In many cases inspections have revealed crushed or clogged pipe. Poor pipe condition does not automatically mean there is a high probability of an unfiltered exit. Evaluate filter and drain envelope and perforations for no erosion, some erosion, and continuing erosion criteria
Drain pipe condition	Thoroughly inspected drains with no problems (breaks, cracks, roots, material accumulation, etc.)	No inspections have been performed – significant uncertainty	Inspections indicate problems with drains (e.g. broken pipe, poor joints, evidence of material transport – much more likely if impermeable zone has been eroded).	
Drain pipe design	Good design typically including filter sand and drain rock	Details on drain design not available	Poor design details; lack of proper filter and drain elements	
Drain pipe construction	Good construction details and records		Poor construction details	
Drain pipe outflow	Clear flow; no evidence of material transport		Evidence of material transport in flow.	
Characteristics of filter and drain envelope	Designed filter and drain envelope that meet no erosion criteria and are of sufficient thickness to prevent failure and minimize construction defects	Gradations of filter and drain envelope not available.	No drain envelope	

<u>Notes on use of Table:</u>

1. Table is intended to provide guidance on the probability of continuation of internal erosion, or the probability of an unfiltered exit. Unlike with the "initiation" tables, there are no historical average base rates to compare relative probabilities. The more likely and less likely factors can be considered qualitatively, and can be applied when there is very little information (e.g. gradations) available for a quantitative estimate. The neutral factors listed in the table are factors that have a small influence on the likelihood, or factors that could equally increase or decrease the likelihood of continuation. Neutral factors do not automatically imply a 50% probability.

2. The probability of continuation, or continuing erosion, is estimated by relying heavily on the evaluation of base soil gradations, filter gradations, and calculated erosion boundaries, as described by Foster and Fell (1999, 2001).

3. Some factors listed on the table are more critical to continuation of internal erosion than others. In general, more influential factors are listed towards the top of the table and less influential factors are listed towards the bottom.

4. For some factors, the "More likely" column also includes factors that would make the probability "much more likely."

<u>References:</u>

Draft Risk Analysis Methodology Appendix E (2000), Estimating Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams, version 2.4, Bureau of Reclamation, Technical Service Center, Denver, CO. August 18, 2000. (This document was never finalized; it was superseded in 2008 by Dam Safety Risk Analysis Best Practices Training Manual, Chapter 24.)

Fell, R., C.F. Wan, and M. Foster (2004), "Progress Report on Methods for Estimating the Probability of Failure of Embankment Dams by Internal Erosion and Piping," University of New South Wales, Sydney, Australia. UNICIV Report 428. 2004.

Foster, M.A. and Fell, R. (1999), "Assessing Embankment Dam Filters Which Do Not Satisfy Design Criteria," UNICIV Report No. R-376, School of Civil and Environmental Engineering, University of New South Wales. ISBN: 85841 343 4, ISSN 0077-880X.

Foster, M. and Fell, R. (2001). Assessing Embankment Dam Filters Which Do Not Satisfy Design Criteria. J. Geotechnical and Geoenvironmental Engineering, ASCE, Vol.127, No.4, May 2001, 398-407.

Bureau of Reclamation (2011a). Design Standard 13 Embankment Dams, Draft Chapter 5, Protective Filters. October 2011.

Bureau of Reclamation (2011b), Dam Safety Risk Analysis Best Practices Training Manual.